N83 19256

OPERATING EXPERIENCE WITH FOUR 200 KW MOD-OA WIND TURBINE GENERATORS

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The objective of the Mod-OA wind turbine project is to gain early experience in the operation of large wind turbines in a utility environment. Four of the 200 kW horizontal axis wind turbines, designed by the Lewis Research Center of the National Aeronautics and Space Administration, have been built and installed at utility sites. Since the first installation in 1977, the machines have accumulated 25,000 hours of operation, and generated 2,500 Mwh f energy. The Mod-OA wind turbines are a first generation design, and even though not cost effective the operating experience and performance characteristics have had a significant effect on the design of the second and third generation machines developed in the Federal wind energy program. The Mod-OA machines have been modified as a result of the operational experience, particularly the blades and control system. The latest machine installed operated nearly 6000 hours during the first year of operation, achieving an availability of 80%, and average plant factor of nearly 0.5, while producing 850 Mwh of energy.

This paper discusses the machine configuration and its advantages and disadvantages, particularly as it affects reliability. It also describes the machine performance, both availability and power output characteristics.

INTRODUCTION

Wind energy systems have been used for centuries as a source of energy for man. The applications have ranged from pumping water and grinding grain to generating electricity. These machines have generally been small, but at times considerable interest, both in the United States and Europe, has existed in developing large wind driven generators. However, interest in these systems has declined because they were not cost competitive with the fossil fuel systems of that era.

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The recent changes in the energy situation have made it necessary to develop alternative energy sources. Wind energy is one of the most highly developed forms of solar energy, and may be a viable alternative energy source.

The Federal Wind Energy Program was established to enable research and development on the many applications and concepts of wind energy systems. This program originated at the National Science Foundation and is currently directed and funded by the Department of Energy. This program is designed to provide the continuity and sustained research and development effort generally lacking from the previous privately funded ventures.

One phase of the program is to develop the technology necessary for the successful design, fabrication, and operation of large, horizontal axis wind turbine systems. This phase of the program is managed by the Lewis Research Center of the National Aeronautics and Space Administration. The Mod-OA machines are the first wind turbines placed in utility operation under this program. The objective of this project is to obtain early operation and performance data while gaining initial experience in the operation of large horizontal axis wind turbines in typical utility environments. These are the first wind turbines in 30 years to operate routinely on a utility grid. The key issues to be addressed through these operations include:

- Compatibility with utility grid.
- Demonstration of safe unattended operation.
- Wind turbine reliability and maintainability.
- Operations and maintenance support.
- Public and utility reaction and acceptance.

The heart of the Mod-OA project is the field operations. Machines are installed in four utilities of greatly differing size, technical capability, climate, geographic location, topography, and wind resource. The operations, routine maintenance, and troubleshooting and repair are performed by the utility as completely as possible. This approach provides the best simulation of eventual commercial operations. Although these first generation machines are not being operated for the prime purpose of producing power and thereby demonstrating commercial usefulness of these machines, they are maintained in a normal utility manner when possible. The major exception to this maintenance procedure is that major failures result in lengthy shutdowns for analysis, redesign and modification. Thus the operations represent a mix between utility simulation and experimental operations.

This report documents 25,000 hours of Mod-OA operational experience. The characteristics of the wind energy generated, the machine performance, and the subsystem strengths and weaknesses are

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discussed. The report also presents an assessment of the project success in fulfilling its goals and objectives.

The Mod-0A machine is based very heavily on the Mod-0 design, so an understanding of the origins of Mod-0 is necessary. In 1973, when it was decided to build a research wind turbine to be known as Mod-0, the size, power rating, and basic design were chosen rather arbitrarily. A literature search did not locate substantial technical design information. Several persons who had been involved in wind turbines before were contacted, and limited help was received, but they were generally unable or unwilling to provide much specific help. The Mod-0 turbine was essentially a fresh start in an unknown technical field.

The machine was to be "large," but not so large that size became a major hindrance. It was not designed to be cost effective, but rather a build it strong enough to last philosophy was used. It was a laboratory type experiment, containing an extensive data system and operated by experienced personnel under controlled conditions and carefully monitored.

The decision to install wind turbines in the field came almost simultaneously with the initial operations of Mod-0. The design was to be upgraded slightly, therefore the name Mod-0A, and installed at field sites as soon as possible. Basically the power rating and, therefore, drive train strength, was increased, and automatic control and safety systems were added. The first Mod-0A installation was completed two years later, and the first large wind turbine to be installed on a utility grid in the U.S. since WW II began operations.

CONFIGURATION

A cutaway view of the Mod-0A nacelle is shown in Fig. 1. The machine is a two blade downwind configuration, using laminated wood-epoxy blades. The hub houses the full span hydraulic pitch mechanism and spindle bearing, which support the blades in a fixed coned position. The low speed shaft, to which the rotor is attached, is supported by two rolling element bearings. The 3 stage parallel shaft gearbox has a hollow input shaft through which the electrical wiring and pitch actuator hydraulic supply line pass. The synchronous alternator is coupled to the gearbox through a v-belt drive, which allows rotor speed changes, and a fluid coupling which provides drivetrain softness and damping. A disc brake is incorporated, on the high speed shaft of the gearbox, for maintenance and emergency shutdown. The bedplate is a box beam structure, and the nacelle housing is fiberglass. The yaw drive is electric, and uses dual motors and gearing to provide sufficient torque. A disc brake provides yaw axis stiffness and damping. The tower is a stiff 4 leg truss design, bolted to the reinforced concrete slab foundation. The switchgear, microprocessor based control system, safety system, and data systems are located in the control room located beneath the tower. A detailed description of the machine design is given in Ref. 1.

The Hawaiian machine is slightly different in that the v-belt drive to the generator is eliminated, and the yaw drive is hydraulic (Ref. 2, 3).

SITE DESCRIPTION

The machines, shown in Figure 2, are identified as Mod-OA1, 2, 3, and 4 corresponding to the order of installation. Mod-OA1 was installed in late 1977 in Clayton, New Mexico. The Clayton utility is municipally owned, and isolated from other systems. The power plant, primarily natrual gas fueled, supplies from 1 to 3.5 Mw to the town of approximately 3000 people. The plant is located approximately 1/2 mile from the wind turbine, and personnel are available 24 hours a day to service the wind turbine.

The second installation is on the Island of Culebra, Puerto Rico, and was completed in mid 1978. The Island is located 20 miles off the coast of mainland Puerto Rico. Electric power is supplied from the mainland thru an underwater cable. The personnel supporting the wind turbine are primarily located in San Juan, and travel to the island by airplane as required. The utility response to wind turbine faults is thus basically limited to a single shift operation, and usually involves a one day delay.

The third installation was completed in mid 1979 on Block Island, Rhode Island, located 12 miles off the coast of Rhode Island. The privately owned utility, isolated from other electrical systems, serves the population of approximately 300 year around residents, and up to several thousand persons during weekends in the summer. The load varies from approximately 250 kW to over a megawatt. The power plant, located a few hundred feet from the wind turbine, usually operates a single diesel generator at a time. The power plant is attended 16 hours a day. Personnel are available to support the wind turbine for one shift, but can usually respond rapidly if needed.

The fourth machine is located at Kahuku, the north side of the Island of Oahu, Hawaii. This site is 45 miles from Honolulu, where the investor owned utility is based. Personnel assigned to the machine are available 16 hours a day, including weekends. The site is in an area currently being developed for a multimegawatt wind turbine farm.

The environmental conditions at these sites also vary radically. The Clayton, New Mexico site has temperatures from 0°F to 100°F. Icing conditions are common in the winter, but the site is very dry typically. The winds are above cutin two thirds of the time, and exceed cutout 50 to 100 times a year. There are strong dinural variations, with very smooth night winds.

The Culebra site is a coastal tropical trade wind situation. There are minimal temperature variations, and the wind is smooth, and rarely above 30 mph except during hurricanes. Wind direction is also nearly constant. Corrosion from the salt laden air is severe, as at Block Island and Hawaii.

The Block Island site has temperature variations slightly less extreme than Clayton, but higher humidity and rainfall. The average wind is slightly lower than Clayton, but much gustier, and is above cutout more often.

The only significant difference between the Hawaii and Culebra sites is the wind velocity. The wind at Hawaii is above cutin over 90% of the time, and above rated far more than at any other site.

UTILITY INTERACTIONS

One of the early concerns with wind energy was that the variable wind turbine output would not be compatible with the utility. Also, would there be any unusual constraints on the interconnection to the utility. A goal of the Mod-OA project was to resolve these issues.

The compatibility of wind energy with a utility has a significant effect on the value of each kilowatt hour (kWh) generated by the wind turbine. If the wind energy contribution has a neglible effect on the utility, as has been the typical case with Mod OA installations, the value, per kWh, is the greatest. However, if the utility has to adjust its dispatch strategies, spinning reserve requirements, and voltage or frequency control, the value of the wind energy decreases. Also to be considered are the possible increases in maintenance and decreased generation efficiency resulting from greater load swings or off-optimum operation of the generation equipment.

Although the addition of wind energy may require changes in power generation strategies and costs, they may be economic questions considerations and not effect power quality. What the utility supplies to the customer is a voltage, of well defined amplitude, waveshape, and frequency. And wind turbines, while generating power, do little to support, and may even hinder, the maintenance of voltage amplitude or frequency. All large wind turbines at this time use conventional generators and thus do support waveform control. But even waveform support may become a factor as advanced designs may incorporate inverters.

The Mod-OA installations have created no significant interface difficulties. In Hawaii and Puerto Rico, the penetration is less than .1%. The Island of Culebra, Puerto Rico, is small, but it is tied thru an undersea cable to the main island grid. In Clayton, New Mexico, the wind power penetration can reach 20%, but does not effect utility operations (Ref. 4). Increments of diesel power which could be added to or taken off line are still large compared to the wind power, and in fact, if a single diesel is used, its overload capabilities are sufficient to sustain the grid if the wind turbine output would be lost. And maintenance levels and efficiencies have not apparently been changed by the introduction of wind power, nor has the quality of the power supplied by the utility decreased.

The wind energy penetration at Block Island, however, is very high and the interface has been a problem. During the winter, the penetration levels exceed 50%, and have averaged 15% over a month. At this site, the generation equipment in operation has been varied due to the wind turbine, and the effects have been significant enough that the fuel efficiency of the diesels does decrease, the maintenance increases, and the power quality delivered decreases. These are effects on a small utility with a single machine and massive penetration, and do not directly predict the effect of several large farms on a large utility. However, the interface requirements for some of the planned and proposed systems will not be insigificant as has generally been the case in the Mod-OA program. The economics of wind energy assume that like base generation, wind energy will be used whenever it is available. But unlike base generation, the output is highly variable and unpredictable. Each new generation technology, whether hydro, diesel, steam turbine, gas turbine, or nuclear, required new operational strategies, but perhaps none were as "different" as wind. The following section shows the output characteristics of the Mod-OA wind turbine to help define the interface requirements.

The interconnection to the utility grid uses a transformer to convert the 480 volt generator output and auxiliary load buses to the utility grid voltage, 2.4 to 12 Kv in these installations. A reclosure for isolation and grid fault protection is connected between the transformer and the utility grid. This interconnection does not require any abnormal line stiffness, and is typically made on an existing feeder circuit.

Mod-OA wind turbines operate in a VAR support mode, and as a power source as available from the wind. Thus the output is best characterized by the output current or power, both the real and reactive components. The actual effect on a utility is then determined from the utility system impedance and voltage and frequency control gains and response rates.

Output voltage, that is excitation control, on the Mod-OA is a fast, inner loop on voltage and an outer loop on VARS, typically controlling for 90 KVAR leading. This mode was chosen to provide generator overexcitation to prevent slipping out of synchronism. VAR generation provides power factor correction for the utility and is, therefore, generally advantageous. In practice, staying in synchronism has never been a problem, so VAR level could be set based only on utility needs. Output voltage fluctuations have not been a problem on these machines, and has never been measured with transducers having enough resolution and response rate to show any voltage fluctuation. Additionally, other wind turbines have operated in constant voltage, constant power factor modes, and with induction generators without causing unacceptable voltage fluctuations.

Power output fluctuations, besides causing possible voltage fluctuations, require other generators to change power level to compensate and maintain frequency control. The power fluctuations resulting from wind generators are so unlike the normal generation that wind generation is often treated as a (negative) load. The power output traces shown herein are for OA wind turbines at various sites, but are generally applicable to all turbines. The absolute amplitudes would of course be different. The frequency content would also change.

The results shown illustrate typical behavior over several time spans. At one extreme, power variations with a frequency content of several hertz can be seen. The other extreme shows data based on weekly averages.

There are four separate identifiable components to a Mod-OA wind turbine power spectra. In general, these apply to all wind turbines, but the characteristics certainly vary. The four components are: a power impulse caused by blade passage behind the tower, the characteristic introduced when the machine is above the rated wind speed and controlling blade pitch to regulate the power output, the power variation in direct response to wind variations when operating below rated wind, and the start/stop transient as the wind traverses the cutin/cutout criteria. These components are listed in the order of decreasing frequency content, and generally in the order of decreasing interest and concern.

The shortest time spectra plot shown in Figure 3A illustrates the blade passage phenomena, the so-called 2P or two per rev for a two-bladed rotor. The impulse is a 10-50kW p-p variation depending on power level and wind shear. The prime cause of the 2P in these machines is the tower shadow effect on the downwind rotor. Changes in tower design, teetering, greater damping, more blades, and upwind configuration will effect the amount of this component. The amplitude and frequency appears somewhat random in this figure, and unsymetrical between blades, due primarily to the machine resonances and wind gusting. The 2P variations are more pronounced in Figure 3B. The 2P variations are important to the machine designers because they are a source of cyclic stress and may be the design drivers for damping and peak torque criteria. To the utility, it may represent a source of voltage fluctuation, but is too fast to cause any effect on frequency control. In the Clayton operation, it tends to act as a "dither" signal for the diesel governors, and actually improve the frequency control by reducing the deadband. The 2P effects would be integrated out in a farm situation where the machine rotors would typically be out of phase with each other.

The second component of power fluctuation is illustrated in Figure 3B, where the wind turbine is controlling pitch to regulate power. The 2P is very obvious in this figure, but the component of interest is the power variation about the 200kW setpoint in response to the wind and pitch angle changes. The controller action is a proportional and integral control based on the power signal. The mean power level, based on a per revolution average, varies about ± 25 kW about the 200 kW setpoint. clipping caused by the recorder is limiting the peak signal to 230 kW in this figure. Actual peak power is approximately 250 kW worst case. The gusting during this data case was rather severe, approaching 5 mph/sec. A longer term case is shown in Figure 3C. The mean power is very constant, the variations are due to the 2P, and wind gusting and controller response.

The peak powers and fluctuations under these conditions generally size the strength of the drive train components, and are thus critical to the machine designers. It also is of great interest to the utilities, but possibly because it is definable and controllable and thus more easily meaningful to discuss than the next case shown. However, the frequency components generated at above rated power should integrate out in a farm, if they don't cause interaction between the machines.

The most common wind turbine operating mode is below rated power. And present designs are tending toward higher rated powers per swept rotor area, thus raising the rated wind speed. Figure 3D is a 6 hour power trace in smooth winds with the 1P and greater frequency components removed. During this period, the machine ran continuously with the output ranging from nearly 200kW to slightly below zero. (The cutoff criteria is -10kW average.) Other typical cases are shown in Figures 3 E, F, G, H. Figure 3E is the ideal but rare case where the machine runs continuously at rated power. Figure 3F is more typical with operation above rated part of the time and below rated part of the time. Figure 3G is steady below rated operation. These are night winds on the plains or trade winds. The final case is an extreme shown in Figure 3H. In 5 hours about a storm front, the machine shut off on low winds before and after the storm, and in high winds during the storm. This operation, although infrequent, and fully automatic, will not filter out significantly in a farm of wind turbines, and will require rapid dispatch adjustment.

The final component of the wind turbine output characteristics is the start/stop cycle. In low winds the transition is very smooth and causes no perturbation in the utility operation, but the cycles may be frequent. Figure 4A contains 4 cycles in less than an hour. However, the Clayton machine typically averages 2 hours per cycle, and at other sites the machines have exceeded 100 hours continuously.

The high wind cycle, as shown in Figure 4B, is much more infrequent, 100 per year, but more severe. The power decreases and increases at approximately 25kW/sec.

MACHINE PERFORMANCE

The machine performance is basically a discussion of hours of operation or energy generation. Although the 25,000 hours of operation have produced extensive data, a meaningful analysis is complicated by the effects of the experimental nature of the program. This section discusses the actual and predicted performance of the machines, the major outages, and the trends and effects of ongoing modifications.

The simplest description of the performance is given in Fig. 5. This curve shows the performance in a steady state mode, that is it does not contain any information about start-up/shut-down times, hysteresis about the cutin/cutout wind speed, or the responses to gusts. The curve also ignores temperature effects, yaw error, and wind shear variations for example, and implies 100% machine availability. All these factors must be accounted for in determining annual energy production. However, the curve of Fig. 5 can be, and has been, verified with a relatively small, several hour, data sample.

Verification of the actual versus predicted machine energy is far more difficult. Thus the measure of machine performance is not stated as an energy capture percentage based on annual energy available, which would be all encompassing, but on the components parts. The major components are the aerodynamic efficiency, drive train efficiency, machine availability, yaw pointing accuracy, start/stop losses and cutin/cutout setpoints or parameters. And these components are interactive. For example, reducing the cutin wind speed tends to increase the startup time. Energy generation would increase, as would sync time, but average power would decrease. And the likelihood of not starting satisfactorily increases, resulting in decreased availability. Thus, although reducing the cutin wind speed helps energy capture, it is very difficult to quantify the improvement. Meanwhile other easily measureable and understandable performance parameters deteriorate. Except to those closely connected with the program, many of the control system improvements made on these machines, for example, do not appear to have had as much effect as has actually occurred due to offsetting effects of changes like cutin/cutout criteria.

One measure of the machine performance as an energy source is shown in Fig. 6. The energy production of the four machines is plotted versus calendar time. The steepest slope portions of the lines represent excellent machine performance (primarily availability) and good winds. The horizontal sections represent prolonged outages.

These outputs represent average plant factors (output compared to wind turbine rating) of 0.1 to 0.15 for Clayton, Culebra and Block Island, and .5 for Hawaii. Deleting the periods of complete machine outage due to blade replacement at the sites (none at Hawaii) and the part time operations at Block Island, would put the average plant factor in the .2 to .3 range for the first three machines. Part time operations at Block Island were required due to potential TV interference before a cable TV installation was completed. Thus for the first four months the machine was only operated 40 hours per week. Although the theoretical energy capture at these sites has not been computed for the entire period, spot checks have shown a good correlation if availability, start/stop losses, and yaw error and other minor effects are taken into account. Availability is the major factor.

The availability of the Clayton machine is shown in Fig. 7A. Several trends do exist in the data. First, the long term average availability has not changed much since initial operations. However, the shorter term averages, 1-2 months, have improved. During the first year there were many failures, both major and minor. Both the utility and NASA responded rapidly to failures, but neither had the experience to make rapid repairs. Thus there were no excellent (high 90's) periods, but also no long total shutdowns. As the program emphasis changed, failure reponse became slower, and more analysis was done before operations resumed. However, the utility's capabilities were greatly improved, so more repairs were done using local crews, and less lost time. Also, machine improvements were being made so there were fewer major or minor failures, except for blades. As a result, there are many more excellent weeks, and fewer mediocre periods. However, the total outages, although no more frequent, lasted far longer. A graphic demonstration is shown in Fig. 8, where the weekly availability, neglecting the weeks of total outage, has risen substantially, and the "typical good" week has risen from the low 80's to the high 90's.

The availability improvements, Fig. 7B,C, are more dramatic for Culebra and Block Island. Both sites have had one major shutdown for blade replacement or repair, but there is also a marked rise in typical week availability. Neither site has utility personnel available 24 hours a day, and therefore minor problems cause significant outages. The availability improvement primarily reflects the decrease in "glitches" due to control system improvements. There have been very few major failures at either of these sites. The Clayton operation is indicative of operations with a local repair crew, on 24 hour call, which might simulate farm operation. In contrast, the Culebra situation is a remote, inaccessible installation which must run in an unmanned fully self-sufficient mode.

The Hawaiian machine availability, Fig. 7D, has remained quite high throughout its life, and averaged 0.8 for its first year of operation. Wind power has a high priority in that region, and the combination of high utility capability and support at all levels and the machine improvements developed from the experience at the other sites has made this machine very successful.

At all sites, the utility must be given much of the credit for the high availabilities. The personnel working on the machines are typically diesel mechanics, yet they perform sophisticated repairs and troubleshooting on complicated systems. Their enthusiasm and personal commitment to this experiment has been a key element in its success.

Component Experiences

A detailed discussion of the failures and resulting modifications is outside the scope of this report. However, this section covers the general areas that have been significant in the operations.

The blades have been the greatest single problem in this program. The original aluminum blades were not expected to be 30 year life low cost components. But the actual life, generally about 1000 hour/per repair, was much less than expected. The basic cause was a design deficiency in one area. After an iteration of repairs, the modifications developed were very successful when applied to an undamaged blade. The Culebra wind turbine operated over 4000 hours without repair. The greatest improvement, however, is the result of the low cost blade program, resulting in the wood epoxy blades operating essentially faultlessly at 3 sites with over 10,000 hours cummulative running, and the fibreglass blades to be tested at Clayton.

The rotor hub has required repairs, but always in parallel with blade repairs, and thus has not affected the availability. Due to the high loads encountered in a rigid hub, the pitch axis bearing design is difficult. The early designs did not maintain preload, and the pitch control gears wore rapidly. These problems have apparently been solved through minor redesign and upgraded lubrication requirements. No further hub modifications are anticipated, although the current lubrication requirements are undesireably high.

The drivetrain has been essentially troublefree except at a single site. The original alternator design was not sufficient for the belt drive configuration employed. This led to a bearing failure at Clayton, and redesign of the alternator drive-end bearing. However, the alternator shaft was damaged by the bearing failure, eventually requiring replacement of the alternator. The bearing was replaced before failure at the other sites, and the 4th machine is a direct drive configuration eliminating the problem. Also, the fluid coupling has failed repeatedly at Clayton. These failures were probably accelerated by the alternator failure, but it was not the sole cause. The fluid coupling is not mounted according to the manufacturer's specifications, and as a result goes thru resonance every startup. A strengthened case replacement is now operating in Clayton and may solve the problem. There have been no significant mechanical drivetrain failures at other sites.

The only other mechanical system problem has been the yaw drive. Yaw axis loads are high in a rigid hub two blade machine, and the yaw system can impart high blade loads also. Actual hardware problems in the yaw system have been rare, but the loads are always a concern and several minor modifications have been made to reduce the load levels.

Hydraulic and pneumatic systems are used for pitch control, yaw system damping, and the rotor brake. These systems have been serious problems in that although malfunctions are not frequent, they are not easily repaired. Most problems have been from shifts in component settings, but pump failures, actuator and valve leaks and rotary coupling failures have occurred repeatedly. An upgrading of these systems is reducing the failure rates, but further improvement is necessary.

The control system, including switchgear, safety system, and remote control, has consistently caused the greatest number of shutdowns, but has not resulted in many major outages. Most shutdowns are not the result of hardware failures, and a system reset is all that is required to resume operations. However, at remote sites several hours to a couple days time is often lost. Control system development has proceeded on several fronts and has been the most heavily modified portion of the wind turbine, except blades. These changes have been to: Reduce blade loads, particularly during startup and shutdown; increase energy capture especially through low wind start/stop criteria; decrease the number of false shutdowns; improve the machine protection; provide better more reliable remote control; and ease trouble shooting of the control system. The approach is to perform more tasks with the microprocessor, delete the separate discreet systems used in the original design, and to use improved algorithms to obtain better control.

Extensive development has also been done on the start up procedure. Many energy prediction codes assume no time loss in start up. And although the energy in the start up winds is quite low, the percent of operating time involved can be quite high. During the first year of operations at Clayton, the machine spent approximately 10% of its operating time in start up. The machine would start at 12 mph, and each start took typically 4 minutes. And only 60% of the starts were successful. The other 40% would shutdown and restart automatically without operator action, but the restart would proceed more slowly, and take 6-10 minutes typically.

The start up is now done at 10 mph, less than 60% of the wind energy available at 12 mph, and takes 2 minutes typically. Approximately 10% of the start attempts are unsuccessful, but the restarts are fully automatic and as fast as the normal start up.

The total loss due to start up time is difficult to assess because the winds are so low. Assuming 100 starts per week, 2 minutes per start, and 25 kW average would be made during the lost time, the loss is about 1% at a 12 mph site. The loss would be less at a higher or steadier wind site.

The two and a half years experience and the modifications made during that time have had a marked effect on the system reliability. The MTBF, mean time between failure, was in the order of 200 hours during the first 6 months at Clayton. The comparable period for Hawaii has a MTBF three times as high. The MTBF is based on operating hours, and only counts failures requiring hardware replacement. A more dramatic increase has been in a mean time between incident calculation, where any situation requiring an operator action is recorded, even though such an action may just be pushing a button at the dispatch office. The interval has gone from a few hours initially, with most actions requiring a site visit, to typically 50-100 hours. A major reason that the Clayton availability has not increased as dramactically as at the Culebra-Block Island facilities is that the Clayton utility has always been able to respond rapidly at any time. The other sites, being remote or without 24 hours dispatcher monitoring, are affected much more by minor incidents.

During the next couple years, it is expected that the machines will continue to perform better, and weekly availabilities will typically be above 90%. And due to the blade improvements, major outages are not expected. However, we expect the utility response to decrease as the turbines are no longer the new "engine" in the system. Thus minor failures will have an increasing effect on availability. The infant failures and major design deficiencies are now eliminated, but some middle-age wearout can soon be expected. Overall, the performance is expected to improve, but not markedly, and the maintenace requirements will become more routine.

PROJECT ASSESSMENT

The objective of the Mod-OA project was to gain early operating experience with large wind turbines. The 3 1/2 years and 25,000 hours of operation have fulfilled that objective, have been invaluable to the design of 2nd and 3rd generation machine designs, and the public and utility perception of wind power. Also, the machines themselves, even though 1st generation, are considered very successful. These machines are being watched very closely by utility and alternate energy groups as the best indicator of practical wind energy generation.

There were also specific goals for the project. One goal was to demonstrate unattended failsafe operation. The machines are running unattended, and the protective systems have successfully detected failures before the failures resulted in other serious damage. The unattended operation has had a significant effect on reliability, pointing out the need for very reliable control and fault detection. Two other related goals were investigating the reliability of wind turbine systems and the required maintenance. The wind turbine reliability was initially below the levels required for commercially viable systems, but problem areas and systems have been identified, and generally corrected and the systems changed in 2nd generation designs. However, the high failure rate has provided an accelerated test of the maintenance requirements, particularly the skills and special tooling and crane requirements. Although most fa[illegible] diagnostics are provided by LeRC engineers, most of [illegible] troubleshooting and repair is accomplished [illegible] the utility, generally by regular diesel mechanics and elect[illegible] Most of the diagnosi[illegible] could also be performed by the ut[illegible] if better manuals and troubleshooting guides were available.

A fourth goal was to assess the compatibility with the utility grid. The grid interaction with these machines has been negligible except at Block Island, where the impact has been a very strong function of the utility diesel state of tune. The utility impact characteristics with Mod-OA machines have shown that the interface is not as severe a problem as was expected, and is in general very benign.

The final goal was to assess the public reaction, and may be the most critical issue. And the public should be divided into four groups: (1) the general public as visitors; (2) the residents of the local area; (3) utility personnel from other utilities and (4) the local utility personnel. The first group is the largest. It is estimated that 20,000 people have stopped to look at the Clayton wind turbine. Most visitors have a positive reaction, it looks good, wind energy is a good idea to pursue. Local residents are no longer in awe of the machines, and tend to be proud of having the machine, but pessimistic about its success. This is primarily a communication problem in that they are unaware of how much the machines have run. The pessimism largely disappears when given a few facts. Visiting utility personnel typically are aware of the economics involved, and view the Mod-OA machines as an experiment which can be very useful, but realize that the machine is not currently viable and that improvement is necessary. Their view of the project is very close to the programs intent. The utility personnel involved with the machine are nearly universally enthusiastic, strong supporters of the machines.

CONCLUDING REMARKS

The Mod-OA project was developed to provide early experience in wind power operation in a utility. To date, the machines have operated 25,000 hours, and produced over 2.5 million kilowatt hours, exceeding the production of any other large wind turbines in the country. The machines have provided extensive data to verify the design codes and loads analysis tools, and to characterize wind turbine performance. Although these 1st generation experimental machines are not currently economical power producers, they have been valuable in assisting the technology development in later machines and in assessing public reaction and utility compatibility. The machines have evolved until they are currently reliable energy sources compatible with the utility requirements and capabilities.

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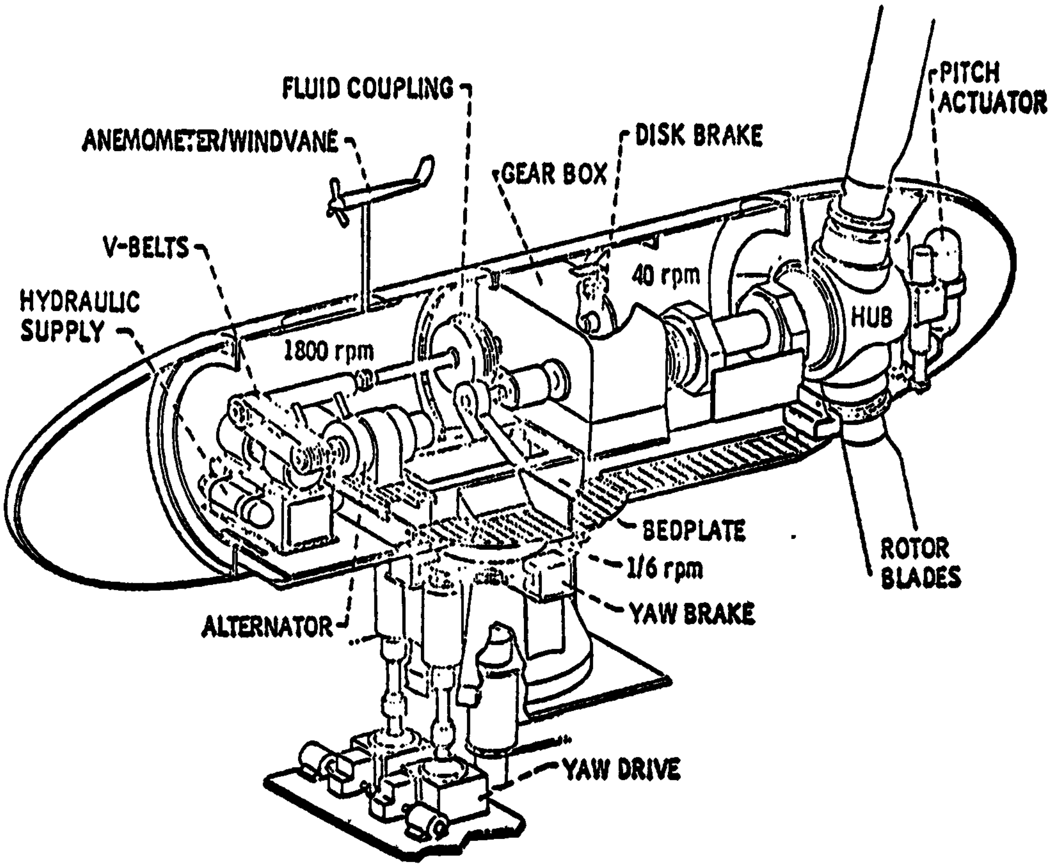
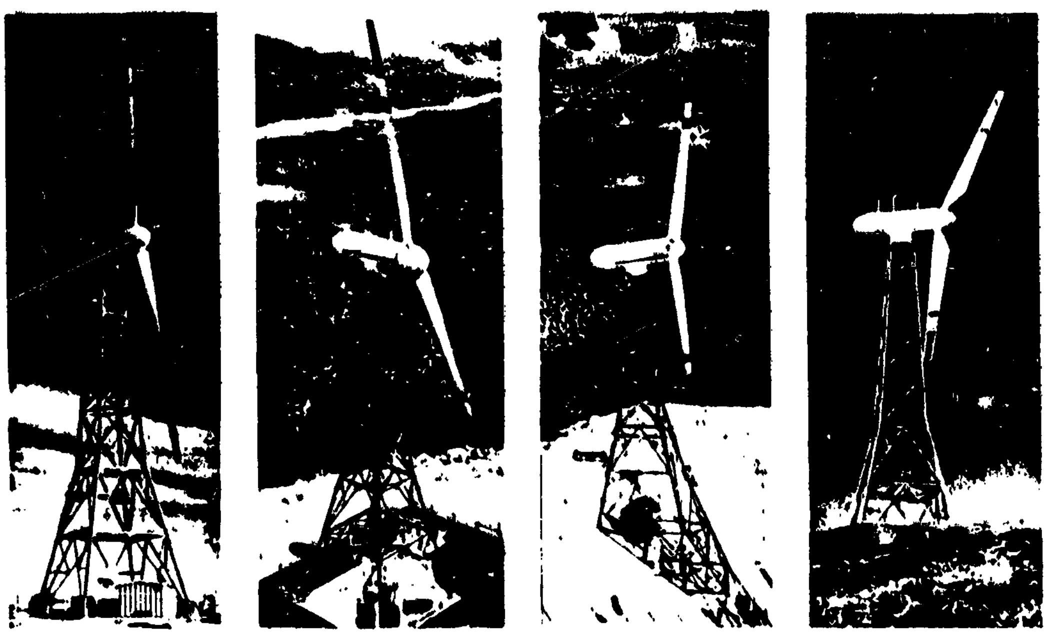


Figure 1. MOD-OA 200 kW Wind Turbine
Schematic of Nacelle Interior



CLAYTON, NEW MEXICO | CULEBRA, PUERTO RICO | BLOCK ISLAND, RHODE ISLAND | KAHUKU PT., OAHU, HAWAII

Figure 2. MOD-OA Wind Turbines

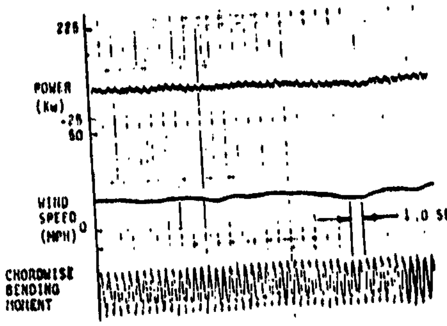


FIG. 3A

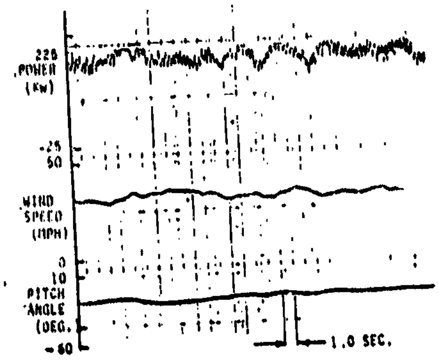


FIG. 3B

FIG. 3C

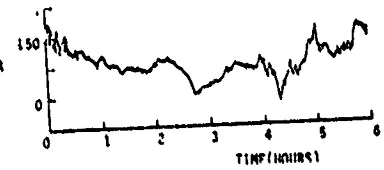


FIG. 3D

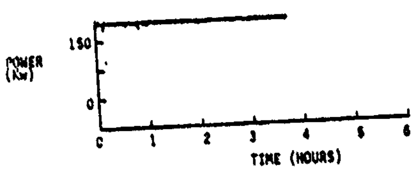


FIG. 3E

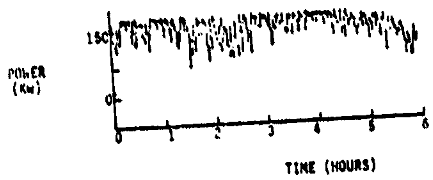


FIG. 3F

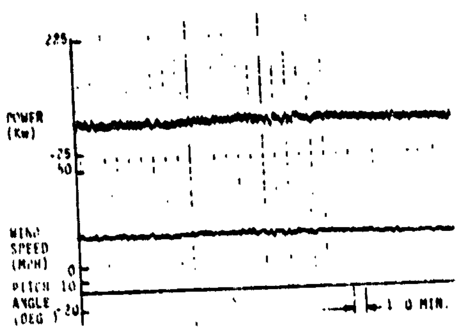


FIG. 3G

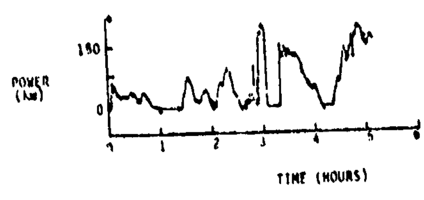


FIG. 3H

Figure 3. Output Power Variations

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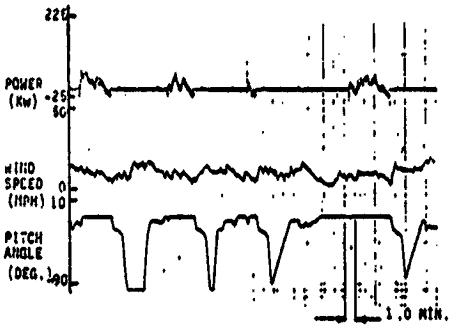

Figure 4A. Low Wind Start - Stop Cycles

Figure 4B. High Wind Start - Stop Cycles

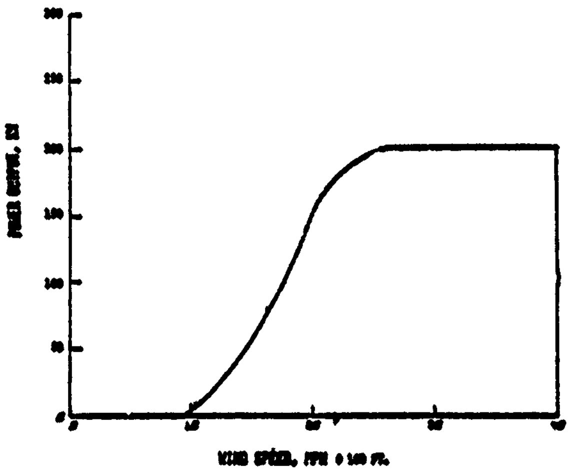

Figure 5. Power Output vs. Wind Speed

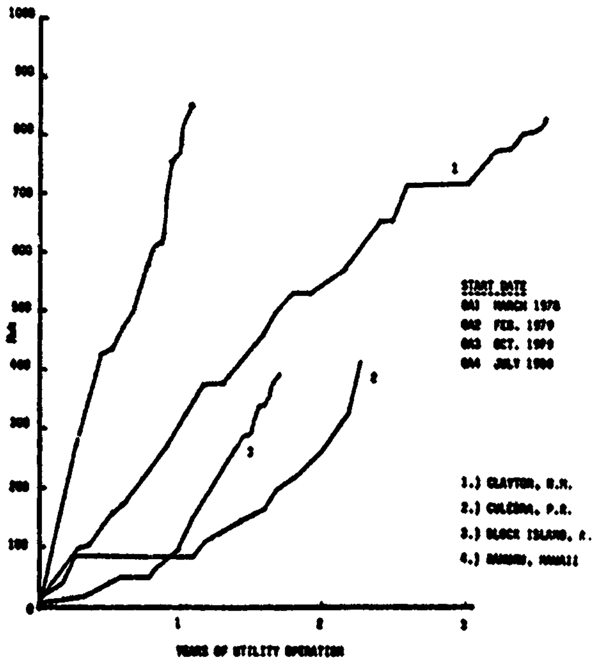

Figure 6. MOD-OA Wind Turbine Energy Production

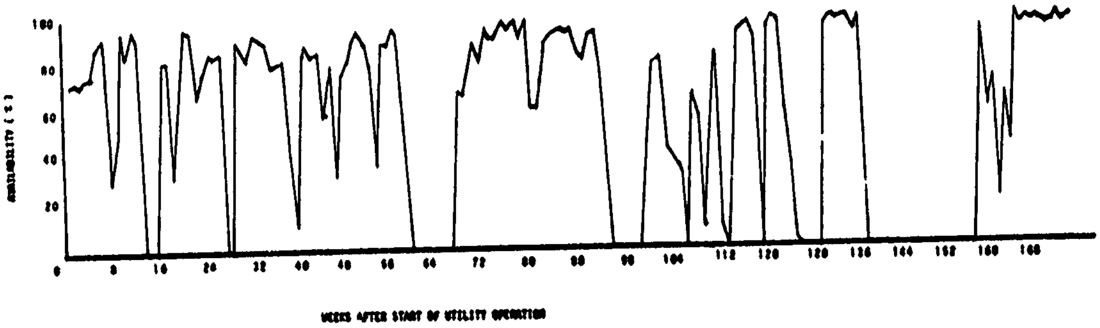

FIG. 7A - CLAYTON WIND TURBINE AVAILABILITY

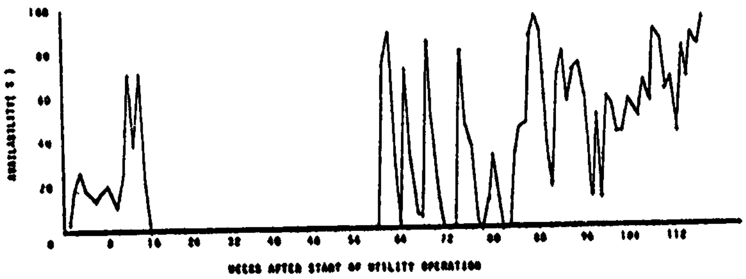

FIG. 7B - CULEBRA WIND TURBINE AVAILABILITY

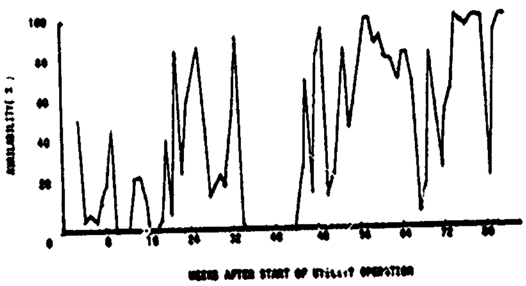

FIG. 7C - BLOCK ISLAND WIND TURBINE AVAILABILITY

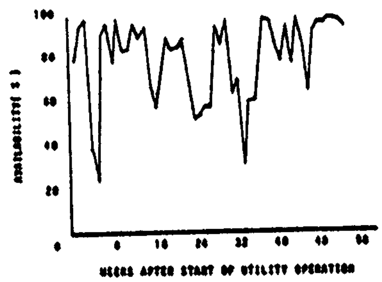

FIG. 7D - HAWAII WIND TURBINE AVAILABILITY

Figure 7. MOD -OA Wind Turbine Availability

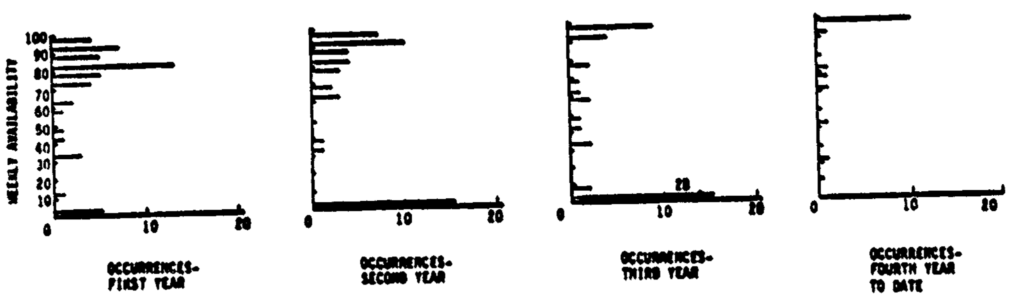

Figure 8. Clayton Wind Turbine Availability